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Emission-Line versus Continuum Correlations in Active Galactic Nuclei

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Abstract. The Baldwin Effect, a negative correlation between emission-line equivalent width and luminosity in active galactic nuclei, is still of interest as a diagnostic of accretion physics nearly thirty years after its discovery. This review examines recent developments in the study of correlations between line and continuum emission in AGNs, as measured both in ensembles and in individual sources.

1. Introduction

A simple but important observational question in the study of active galactic nuclei (AGNs) is whether emission-line luminosities scale in proportion to continuum luminosity for the central source. This topic has been investigated in multiple studies over the past three decades. An early and influential paper on this subject was published by Baldwin (1977), who reported a strong, negative correlation between the restframe equivalent widths for the ultraviolet (UV) lines (particularly C IV λ1549) and continuum luminosity in quasars. Carswell & Smith (1978) referred to this trend as the *Baldwin Effect*, a label thereafter adopted by the AGN community. The Baldwin Effect can be expressed in terms of line luminosity or equivalent width (EW), and both descriptions commonly appear in the literature. An illustration of what the Baldwin Effect means for quasar spectra is shown in Figure 1, which shows a set of composite spectra from Dietrich et al. (2002) for sources binned by luminosity.

Nearly thirty years after Baldwin's original paper, the correlation he reported still remains interesting in relation to BLR physics. Opportunities to study line versus continuum correlations have improved dramatically in recent years, thanks to better and more abundant data. Something I want to emphasize in this review, however, is that the context for understanding the Baldwin Effect has also grown, thanks to the emergence of sophisticated tools such as Principal Components Analysis, and techniques for estimation of black hole masses. While emission-line EWs may seem rather primitive diagnostics, they retain the virtue of being easily measurable, including in cases where flux calibration is sometimes difficult, such as large optical surveys with fiber-fed spectrographs.

Some clarification of the scope of this review is warranted given the varied phenomena that have been tagged with the Baldwin Effect label. The original trend is a correlation between emission lines and continuum luminosity measured from single-epoch observations of multiple QSOs. Studies of individual, variable AGNS have also revealed negative correlations between emission-line EWs and continuum luminosity (L), which Pogge & Peterson (1992) dubbed

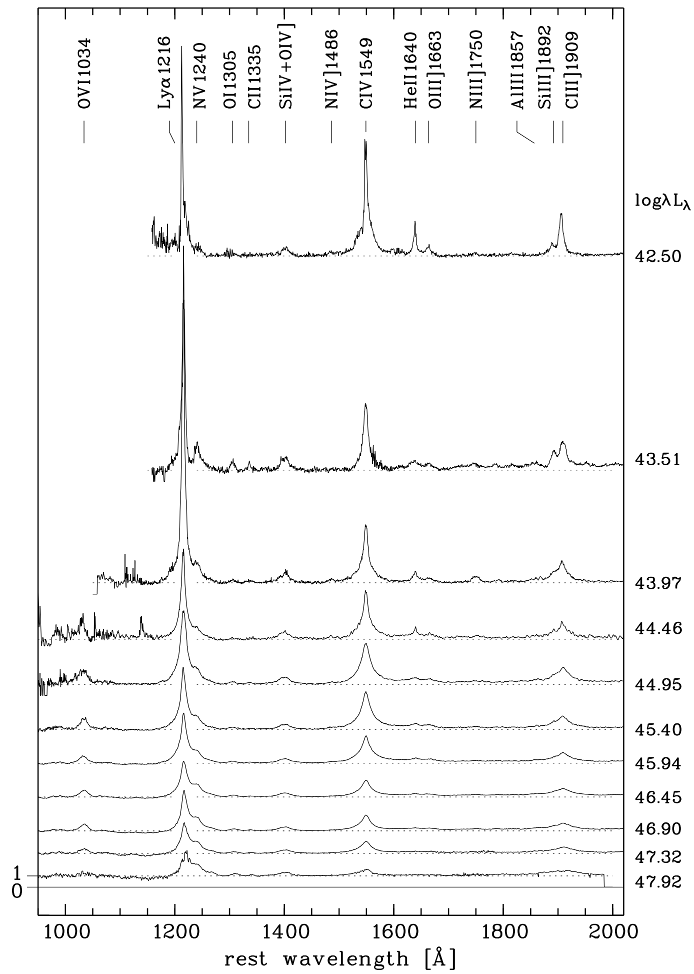

Figure 1. Normalized composite spectra for QSO subsamples binned by luminosity [$\Delta \log \lambda L_\lambda(1450\text{Å}) = 0.5$ dex]. Individual spectra are shown on a common vertical scale, shifted for display purposes (Dietrich et al. 2002).

the "intrinsic" Baldwin Effect to distinguish it from the original ensemble (or "global") effect. While most of the early studies of the Baldwin Effect focused on UV/optical broad emission lines, more recent work has also investigated in some detail correlations between narrow emission-line and continuum luminosities. Improvements in X-ray technology have permitted detailed studies of the Fe Kα line, and there have been a number of claims that this feature shows an "X-ray Baldwin Effect". But claims of a Baldwin Effect have moved beyond AGNs with reports of such a trend in the optical emission lines for Wolf-Rayet stars (Morris et al. 1993) and dwarf novae (Long et al. 2005)[1]. A key point to keep in mind is that the Baldwin Effect is simply an observational correlation; the

[1]To confuse things further, searching in the NASA Astrophysics Data System on the words "Baldwin Effect" will also turn up references to the computer science literature, referring to an idea in evolutionary biology originated by Baldwin (1896).

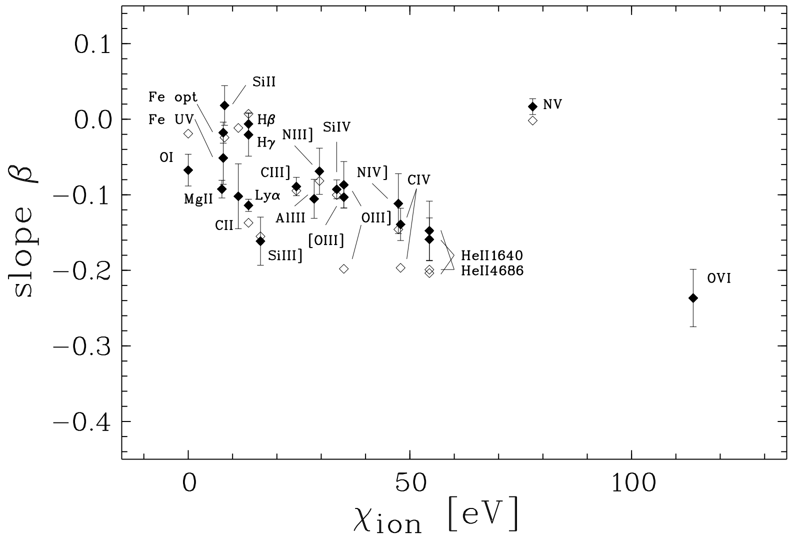

Figure 2. Slope β of the best linear fit in the log EW vs. log L plane for emission lines of the indicated species, plotted as a function of the ionization energy χ_{ion} required to create the ion (Dietrich et al. 2002). Open symbols represent slopes obtained using only high L sources (see Dietrich et al. for details).

physics underlying the correlation may be very different in each of these cases. In this review I will be restricting the discussion to AGNs, and even within these sources the different Baldwin trends (broad lines, narrow lines, intrinsic, X-ray) may have disparate origins. I will also emphasize recent developments; a review of the older literature on the subject and detailed discussion can be found in Osmer & Shields (1999, hereafter OS).

2. The Ensemble Baldwin Effect

2.1. What Do We Know?

By now several aspects of the ensemble Baldwin Effect are well determined. A first point that has generated some controversy in the past is simply that *it exists*. Studies following Baldwin's initial report generally found greater scatter and sometimes little evidence of any trend. It now seems that significant scatter is typical of most AGN samples, and the key to finding the correlation is having a sufficiently large span of luminosity in the sample; an excellent illustration of this point can be found in the study by Kinney et al. (1990), which was among the first to probe AGNs covering 6 orders of magnitude in UV continuum luminosity.

A second aspect of the Baldwin Effect that now seems firmly established is the existence of *different slopes for different lines*. The variation is not random (Figure 2); lines originating from higher ionization species display steeper slopes in the EW versus L diagram (e.g., Espey & Andreadis 1999; Dietrich et al. 2002).

A few lines depart from these trends and merit special mention. Multiple studies have shown that the N v λ1240 EW shows little if any dependence on

L – in other words, no Baldwin Effect, which is particularly noteworthy given the large ionization potential for this ion (Dietrich et al. 2002, and references therein). The most likely explanation for its exceptional behavior is a nucleosynthetic one, since secondary nitrogen enrichment will cause the N/H ratio to scale as the square of the global metallicity; if higher luminosity sources are also characterized by higher metallicity, the selective enhancement of nitrogen in luminous sources may compensate for the processes that would otherwise diminish N V emission as expected from the Baldwin relations (Hamann & Ferland 1993; Korista et al. 1998).

An additional line of special interest is Hβ λ4861. Most studies have shown little luminosity dependence in the Balmer lines, but recent work with large samples has demonstrated a weak *inverse* Baldwin Effect for Hβ: $EW \propto L^{0.2}$ based on the 2dF+6dF surveys (Croom et al. 2002), and $EW \propto L^{0.1}$ using the Sloan Digital Sky Survey (Greene & Ho 2005; see also Netzer & Trakhtenbrot 2007). The tight relationship between line and continuum luminosity means that Hβ can be used as a surrogate for the optical or total luminosity. Since the velocity width of the same line serves as a kinematic tracer of the BLR, this single feature provides the necessary ingredients to estimate the black hole mass $M_\bullet$ in a given source (Greene & Ho 2005; see also X.-B. Wu, this conference).

2.2. Explanations

Several physical explanations have been proposed to account for the Baldwin Effect, and its dependence on ionization. A hypothesis that has gained considerable support is that the continuum shape is luminosity-dependent such that more luminous objects have softer UV/X-ray spectra, resulting in reduced ionization and photoelectric heating in the BLR gas (e.g., Netzer et al. 1992; Korista et al. 1998). In that case the equivalent widths of emission lines diminish at higher luminosity with the strongest effect expected for high-ionization lines, as observed. Independent analyses of AGN spectral energy distributions confirm a luminosity dependence in the continuum that it is at least qualitatively consistent with this picture (e.g., Strateva et al. 2005).

A question that merits careful consideration is whether the Baldwin Effect is actually driven by a relationship between EWs and another fundamental parameter that happens to be correlated with L in typical AGN samples. Specific examples of such a parameter would include redshift z, the Eddington ratio L/L_{Edd}, and $M_\bullet$. Distinguishing which of these properties is a key driver in the correlations is not easy. Testing the dependence of EW on L and z independently requires a sample that fills out the $L - z$ plane; the hard part, of course, is obtaining measurements of low L sources at high z. Progress in this matter has been demonstrated recently by Dietrich et al. (2002), who assembled a large sample from various existing surveys that allows measurement of EW as a function of L at constant z, and EW as a function of z at constant L. The results convincingly demonstrate that luminosity dominates the trend, and any dependence on z is weak in comparison.

Several recent studies have investigated the question of whether L/L_{Edd} is actually the driving parameter for the Baldwin Effect. Estimates of L/L_{Edd} require values of $M_\bullet$, which in turn are obtained from luminosities and emission-line velocity widths, using calibrations from reverberation mapping. Baskin & Laor

(2004) found that EW(C IV) for the PG quasars shows a tighter relationship with L/L_{Edd} than with L. Using a different sample, Netzer et al. (2004) likewise found evidence for a stronger correlation with the Eddington ratio, but using EW(Hβ), where the very existence of a conventional Baldwin Effect appears inconsistent with other studies (see above), a result Netzer et al. ascribe to possible sample incompleteness. Via more circuitous arguments, Bachev et al. (2004) also claim evidence for L/L_{Edd} as the more fundamental parameter underlying the behavior of C IV in particular. Warner et al. (2004) have investigated other lines in the Dietrich et al. (2002) sample, and find evidence for significant correlations in many cases between EW and L/L_{Edd}, but with slopes that are rather different from those seen in the conventional Baldwin diagrams (e.g., a significant Baldwin Effect for N V and an inverse trend for O VI λ1034).

Assessing the relative importance of L, L/L_{Edd}, and $M_\bullet$ in driving the Baldwin correlations is complicated by the fact that these quantities can be highly correlated in typical samples. To address this problem, Warner et al. (2006) have most recently used composite spectra built from subsamples to separate the dependencies on these variables. Their results illustrate spectral variations that result as L/L_{Edd} is incremented while $M_\bullet$ remains constant, and as $M_\bullet$ is incremented while L/L_{Edd} remains constant. In the former case, little change in equivalent widths is seen as L/L_{Edd} varies, while in the latter case, a strong dependence on $M_\bullet$ appears. Their sample overall shows the classical Baldwin dependence on L, but the spectral changes diminish substantially when L is varied for a subsample restricted to a narrow range of $M_\bullet$. In contrast, dramatic line variations are seen as $M_\bullet$ is varied while L remains fixed. In summary, Warner et al. provide strong evidence that $M_\bullet$ is likely to be the fundamental parameter driving EW variations that appear as the Baldwin Effect. This finding has an attractive physical consistency in that more massive black holes are expected to have cooler accretion disks that in turn will produce softer continua, in qualitative accord with the ionization dependence of the Baldwin Effect (e.g., Netzer et al. 1992; Wandel 1999).

2.3. New Approaches

By now, a variety of other trends and correlations have emerged out of the expanding spectral data for AGNs, and to genuinely understand the Baldwin Effect and its implications, we must integrate it into this larger context. Fortunately we also now have tools that allow us in principle to achieve this goal, where in particular I am referring to Eigenvector or Principle Components Analysis (PCA; e.g., Boroson & Green 1992; Francis et al. 1992; Shang et al. 2003). In a multi-dimensional space of measured spectral parameters, PCA identifies eigenvectors that trace the maximal variance in the system, thereby reducing its dimensionality if some of the parameters are correlated. Expressed another way, PCA makes it possible to find patterns in the spectra of large AGN samples, describing in an objective way which among many spectral properties correlate, and how. The hope is that once such patterns are identified, they can point us to understanding what fundamental physical properties are ultimately responsible for defining the observed properties of AGNs.

One of the more comprehensive PCA analyses for AGNs that encompasses both the restframe UV and optical bandpasses is that of Shang et al. (2003).

Their study employs "spectral PCA" such that the measured parameters are values of flux as a function of wavelength in normalized spectra; the resulting eigenvectors then have the appearance of spectra. These eigenvectors are labeled as Spectral Principal Component (SPC) 1, 2, 3, etc. according to their dominance in accounting for the variance in the input dataset. Shang et al. argue that the Baldwin Effect is closely linked to their SPC1, which shows prominent line cores and diminishes in strength as source luminosity increases. A separate SPC, their SPC3, is linked to the "Eigenvector 1" (EV1) identified in optical spectra by Boroson & Green (1992), which those authors argue is driven by either L/L_{Edd} or $M_\bullet$. The upshot is that PCA studies do not draw a strong connection between the Baldwin Effect and either Eddington ratio or $M_\bullet$ as key underlying parameters.

An informative way to probe this issue further is to examine the behavior of Narrow-Line Seyfert 1 (NLS1) galaxies in the Baldwin diagrams. NLS1 galaxies display broad Hβ with relatively small velocity widths, and weak forbidden lines as well as distinctive X-ray properties. Their characteristics overall place them at one extreme of the EV1 sequence and there is considerable belief that they are in a high accretion state with large L/L_{Edd}. Leighly & Moore (2004) have examined the behavior of NLS1s in the Baldwin diagrams for UV lines and find the NLS1s are systematically offset to lower EWs at a given continuum luminosity, relative to broad-line AGNs considered more generally. We might expect the EW trends to show more homogeneous behavior when EW is plotted against L/L_{Edd}, since the expectation is that the NLS1s will slide to the right-hand side of the diagram where EWs are low. But when this exercise is actually carried out, as shown by Warner et al. (2004), the outcome is not so clean. For some emission features NLS1s align with other AGNs in the EW vs. L/L_{Edd} diagram, but for others the NLS1s fall *sometimes below and sometimes above* the full ensemble trend – and notably, the NLS1s do not show the largest L/L_{Edd} values among their sample. Does the latter statement imply that Warner et al. (2004) systematically mis-estimated L/L_{Edd} for NLS1s, due perhaps to their use of C IV rather than the better-calibrated Hβ line in deriving $M_\bullet$? Even if we suppose this to be the case and slide the NLS1 results horizontally in the EW vs. L/L_{Edd} diagrams, these objects remain outliers from the main trend, often with disagreement in different directions for different lines. As noted by Warner et al. (2004), the results suggest that one or more additional parameters beyond L/L_{Edd} are important in defining the spectral characteristics of NLS1s.

To summarize, conventional correlation analyses and PCA to date provide mixed indications of a major role for L/L_{Edd} or $M_\bullet$ in driving the Baldwin Effect. Results shown by Warner et al. (2006) provide strong indications that $M_\bullet$ is in fact a key underlying parameter; confirmation with other samples and by other approaches such as PCA would be desirable.

3. The Intrinsic Baldwin Effect

Multi-epoch observations of variable Seyfert galaxies have shown in many cases an intrinsic Baldwin Effect, i.e. a decrease in emission-line EW as the source brightens in the continuum. The data are sufficient to make a number of generalizing statements about this phenomenon.

A first essential point is that the intrinsic Baldwin Effect invariably has a steeper slope than the ensemble Baldwin Effect; the contrast is nicely illustrated in Kinney et al. (1990; see also Pogge & Peterson 1992). The two correlations are different and may arise from very different causes, a distinction that is not always made in the literature (see OS for further discussion). A second aspect commonly seen in the intrinsic effect is *curvature* – the slope displayed in the log EW vs. log L plane steepens as the source brightens. An example appearing recently is the compilation of UV results spanning more than 20 years for NGC 4151 by Kong et al. (2006).

Ultimately we can understand most aspects of the intrinsic Baldwin Effect, including its slope and curvature, in terms of photoionization theory for the BLR, reflected in the responsivity of the line-emitting clouds as the irradiating continuum varies in intensity. This issue has been explored in detail by several authors (e.g., Gilbert & Peterson 2003; Goad et al. 2004; Korista & Goad 2004; Cackett & Horne 2006). These studies suggest that in the future the detailed luminosity-dependent response of the emission lines can serve as a diagnostic tool for the BLR and its structure.

A specific set of lines with special interest in variable AGNs is the optical Fe II emission. Two recent studies illustrate the continuing uncertainty in Fe II behavior. Wang et al. (2005) measured optical Fe II emission in the variable NLS1 NGC 4051 and found that the Fe II varied with *greater* amplitude than Hβ and the continuum – i.e., Fe II shows an inverse Baldwin Effect. In contrast, Vestergaard & Peterson (2005) reported that the amplitude of variability for optical Fe II in NGC 5548 was only 50% – 75% that of Hβ. Measuring Fe II emission is inherently difficult due to the large number of features and their substantial blending. Further investigations of Fe II response would be of interest given the significant energy carried by these lines and continuing uncertainty about their excitation. Vestergaard & Peterson (2005) have noted that the fact that Fe II responds at all to the continuum already indicates that line fluorescence in a photoionized plasma apparently dominates over collisional heating in exciting the observed emission.

4. The Baldwin Effect in *Narrow* Lines

Information on the luminosity dependence of the narrow emission lines in AGN ensembles has grown significantly in recent years, and there is now clear evidence that at least some of the narrow lines display a Baldwin Effect (e.g., Boroson & Green 1992; McIntosh et al. 1999; Croom et al. 2002; Dietrich et al. 2002; Netzer et al. 2004; Netzer et al. 2006). The best studied feature is [O III] λ5007, although Croom et al. (2002) have compiled extensive results also for [Ne V] λ3426, [O II] λ3727, and [Ne III] λ3869. Croom et al. find a Baldwin Effect for both [Ne V] and [O II], and marginal evidence for a trend in [Ne III].

The narrow emission lines in AGNs originate on vastly larger dimensions than the BLR size scale, and for this reason if not others it is quite possible that luminosity dependence in the EWs may have very different causes for the narrow and broad lines. One likely explanation for the Baldwin Effect that is specific to the narrow lines takes note of the fact that in luminous AGNs, the scale of the narrow-line region (NLR) may become comparable in size to the entire galaxy, with the result that the emission measure of the gas cannot grow further if the luminosity increases; the NLR has run out of gas (e.g., Croom et al. 2002). The NLR that is present may also end up being more highly ionized or partially ejected from the galaxy, which could result in less emission in the optical forbidden lines.

The reduced narrow-line EWs in luminous AGNs have additional potentially significant implications. The existence and numbers of "Type 2" QSOs, i.e. lacking broad emission by analogy with Seyfert 2 galaxies, is of interest for understanding the statistics of BLR obscuration, the true space density of accreting black holes, and the possibility that some QSOs genuinely lack an intrinsic BLR. Finding Type 2 QSOs has proven challenging and often relies on their detection in the narrow forbidden lines. Many luminous Type 2 AGNs thus may be missing from our census if their NLR emission is reduced in relative or absolute terms, as implied by the Baldwin Effect (Croom et al. 2002; Netzer et al. 2006).

The NLR Baldwin Effect also has relevance to the possibility of using nebular lines as tracers of star formation in AGN hosts. Ho (2005) has noted that the weak [O II] emission characteristic of quasars implies very low levels of star formation if standard conversions between L([O II]) and star formation rate (SFR) are applied; if part of the [O II] emission originates in NLR gas powered by the AGN, the estimated SFR for the remaining fraction is even less. The fact that NLR emission appears weak could imply that star formation is suppressed by the influence of the accretion source, or perhaps that star formation is confined to dense, shielded regions with low filling factor. In any case, the Baldwin Effect observed for narrow lines is probably telling us important things about the AGN host galaxies for luminous systems.

5. The X-ray Baldwin Effect

The dominant line in the hard X-ray spectrum of AGNs is the Fe Kα feature, and there is ongoing debate as to whether this feature exhibits a Baldwin Effect. The initial suggestion of such a trend was made by Iwasawa & Taniguchi (1993) based on *Ginga* measurements, and Nandra (1997) subsequently found confirming results using *ASCA*. The advent of *XMM-Newton* and *Chandra* has substantially increased the quantity and quality of Fe Kα measurements for AGNs, and several papers using data from these telescopes have appeared, supporting the existence of a Baldwin Effect in most cases (Page et al. 2004, 2005; Zhou et al. 2005; Jiang et al. 2006) but not all (Jiménez-Bailón et al. 2005). At this conference Stefano Bianchi presented measurements for a new, expanded sample that provide support for the existence of a Baldwin Effect for Fe Kα.

Several explanations have been put forward for the X-ray Baldwin Effect. Since the Fe Kα line originates via reprocessing involving photoelectric absorption in high column density gas, one possibility is that the covering factor of such gas is reduced in higher luminosity sources. A clue to the nature of the reprocessor is provided by the line profile. The *XMM* results indicate that the emission is mostly narrow (i.e., nonrelativistic, with widths of $10^3 - 10^4$ km s^{-1}), suggesting that the reprocessor may be the BLR, the outer accretion disk, or the circumnuclear torus. If the emission originates from the disk, a theoretical prediction consistent with a Baldwin Effect is that luminous sources driven by large accretion rates will produce less Fe Kα emission, as the disk becomes sufficiently ionized that much of the Fe is fully stripped of electrons (e.g., Matt et al. 1993; Nandra 1997). If the line originates from the torus, the observed trend would be a natural consequence of the "receding torus" model in which the inner boundary of the torus moves outward as luminosity increases, so that the covering factor is reduced if the torus scale height remains constant (Lawrence 1991). If Fe Kα is produced substantially in the BLR, the same medium produces the UV/optical lines that show the original Baldwin Effect; a luminosity-dependent covering factor may account for part of the trend, but the inverse correlation seen in some lines (notably Hβ, §2.1) makes this explanation less satisfying.

Other explanations that do not involve a luminosity dependence in the reprocessor structure are possible, however. Jiang et al. (2006) have argued that the X-ray Baldwin Effect is substantially driven by radio-loud sources. In these objects we may be observing an extra X-ray continuum component from a relativistic jet that does not participate in Fe Kα production, so that when the jet component is strong, the source appears more luminous while EW(Kα) appears weak (see also Jiménez-Bailón et al. 2005). Jiang et al. (2006) find that radio-quiet AGNs considered alone display a weak Baldwin Effect in Fe Kα that can be understood as a consequence of variability; if the light-crossing time for the region emitting Fe Kα exceeds the variability timescale for the X-ray continuum, a Baldwin Effect naturally occurs as the continuum goes up and down, and individual sources in an ensemble are measured at random phases. Miniutti & Fabian (2004) note that light-bending effects near a rotating black hole may act to accentuate the observed trend.

The observational situation remains dynamic, as illustrated by S. Bianchi's results presented at this meeting showing a significant X-ray Baldwin Effect for a large sample restricted to radio-quiet objects. Discussion of the X-ray Baldwin Effect and issues related to Fe Kα emission were presented by Giorgio Matt and Tahir Yaqoob, and the reader is referred to their contributions for further details.

6. Conclusions

Considerable progress has been made in recent years in our understanding of the Baldwin Effect and related correlations. Luminosity-dependent EWs are clearly seen in both the broad and narrow lines for AGN ensembles. There are strong indications that the broad-line trends may actually derive from more fundamental correlations with other parameters such as $M_\bullet$ or L/L_{Edd}, although a consensus in the community on this point has not yet emerged. Integrating studies of the Baldwin Effect into more comprehensive PCA analyses is a necessary step to advance this field of inquiry. NLS1 galaxies appear to be outliers from many of the correlations and there is a need to address why this is the case. A theme that has surfaced repeatedly through the Baldwin Effect's history is that the details of sample selection remain very important. Further progress is possible and clearly desirable.

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